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Extruded plastic counters with WLS fiber readout

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Abstract

Extruded plastic scintillation counters with WLS fiber readout are described. For a 7 mm thick counter with 4.3 m long double-clad fibers spaced at 7 mm a light yield of 18.7 photoelectrons/MeV and a time resolution of 0.71 ns (σ) were obtained. A prototype photon veto module consisting of 10 layers of 7 mm thick grooved plastic slabs interleaved with 1 mm lead sheets was also tested, which yielded 122 photoelectrons per minimum ionizing particle and time resolution of 360 ps. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In this paper we report on the performance of extruded plastic scintillation counters with wavelength shifting (WLS) readout and a sandwich module consisting of such counters interleaved by thin lead sheets. These detectors were developed as prototypes of veto detectors of charged and neutral particles for a proposed BNL experiment E926(KOPIO) [1].

The main goal of this experiment is to measure the $K_L^0 \to \pi^0 \nu\bar{\nu}$ branching ratio and determine the complex phase parameter η with a precision of $\leqslant 15\%$ without serious interference from background or systematic effects. The signature of the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay mode is the detection of two photons whose invariant mass is consistent with that of a π^0, and nothing else. The most important part of the experiment is the determination that nothing other than one π^0 was emitted in the decay, i.e. a high efficiency veto of any extra particles. The most difficult mode to suppress is $K_L^0 \to \pi^0\pi^0$ which can simulate $K_L^0 \to \pi^0 \nu\bar{\nu}$ if two of four photons are undetected. It requires an extremely high photon detection efficiency of better than 0.9999 per photon, without excessive loss from random vetoes. Charged particles from K_L decays also should be detected with an efficiency of more than 99.9%. High light yield is needed to satisfy these requirements. Since

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the momentum of the K_L^0 in E926 is determined using a pulsed beam and time-of-flight method, the veto system must have good time resolution of about 200 ps for photon energies of 100–200 MeV while covering a large solid angle around the kaon decay region. The scheme of the proposed experiment is shown in Fig. 1. The complex detector geometry, in which the charged particle veto counters will be installed in a vacuum vessel, and a requirement of 4π solid angle veto coverage make it impractical to use light guides for transporting light to photomultiplier tubes. The large volume of plastic scintillator needed for coverage of a very large solid angle, and the extremely high detection efficiency required to reach the physics goals, make the design of the veto system very challenging. The cost of the veto system is also a very important issue given the detector size.

Lead–plastic scintillator sandwich veto counters are being considered for the barrel veto detector which will have a thickness of 17 X_0 (radiation lengths). To read light from the scintillators, a two-ended wavelength-shifting fiber readout technique will be used [2,3]. The extrusion method allows us to produce relatively cheap long grooved scintillators which are well matched to the WLS fiber readout.

2. Fabrication of grooved extruded plastics

The extrusion technique of long grooved scintillators was developed at the Uniplast Factory, Vladimir, Russia. In the first stage, an investigation was done to determine the optimum dopant compositions for a polystyrene based scintillator. The optimization was directed at reaching the highest light yield. The light yield of small tiles ($20 \times 100 \times 6$ mm^3) was measured with a ^{90}Sr β-source triggered by a reference counter. The scintillation light was absorbed by a multi-clad BCF99-29AA fiber [4]. A paraterphenyl (PTP) concentration of 1.5% and a concentration of POPOP 0.01% were chosen, since the light yield was nearly constant at concentrations of 1.5–2.0% and 0.01–0.05% of PTP and POPOP, respectively, which is in good agreement with the more detailed results obtained in Ref. [5]. The standard composition of 1.5%PTP + 0.01%POPOP provides a light yield of about 80% of the light yield of Bicron BC408 scintillator for the configuration tested.

The samples were manufactured using an extrusion technique which allows us to produce very long (> 4 m) grooved plastic slabs with a good reflective surface. A scintillator is extruded through a spinneret and a triple roll calendar equipped with an additional gear to form the grooves. The extrusion line provides a homogeneous thermal

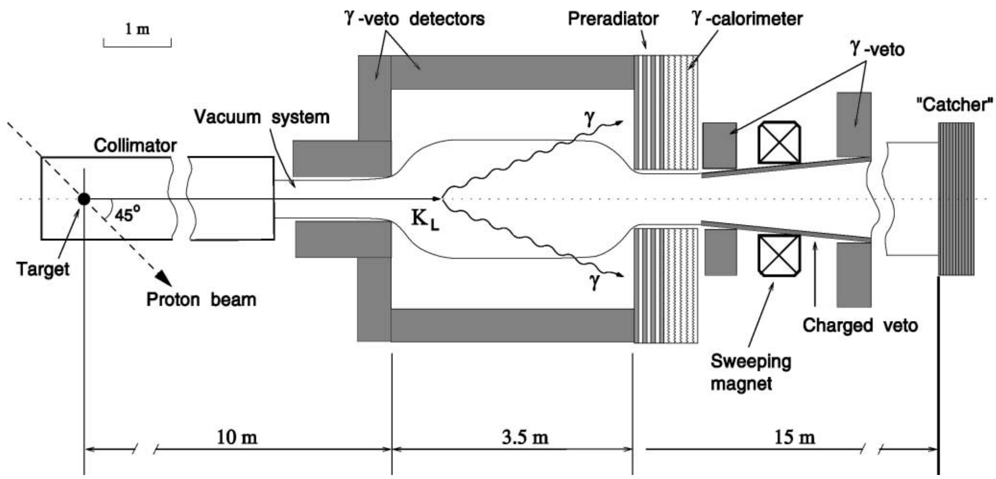

Fig. 1. Scheme of the proposed BNL experiment E926 (KOPIO) to measure $K_L^0 \to \pi^0 \nu\bar{\nu}$.

mixing of polystyrene pellets and fluorescent dopants at a temperature of 160–240°C. During squeezing-out a scintillator polymerizes isotropically over a volume. The extrusion velocity depends on the plastic thickness and varies from 0.15 to 0.6 m/min. Simple tests with small scintillators and direct plastic-PMT contact showed that an extruded polystyrene gives the same light yield as a molded one. Transparency of the extruded scintillator is homogeneous in all directions, and the light attenuation length was measured to be about 30 cm in a 5 mm thick extruded strip [6]. The extrusion technique does not provide high precision control of dimensions. The slab width tolerance is required to be 0.1 mm to avoid gaps between counters, which adversely affect the detection efficiency. A laser cutter trimmed the width to 150 ± 0.1 mm. For technical convenience, the tested 7 mm thick samples were produced in lengths of 0.5–2 m, with widths of 150 mm. The profile of the 1.1 mm deep grooves deviated slightly from an ideal U-shape during plastic hardening.

Instead of using a wrapping material for a reflector we applied a novel technique: the scintillator is etched by a chemical agent that results in the formation of a micropore deposit over the plastic surface, following which the diffuse film is fixed in a settling tank. The deposit thickness depends on the etching time. An advantage of this approach over the commonly used white diffuse papers is the almost ideal contact of the reflector with the scintillator. Moreover, it provides the option of gluing a lead sheet to the plastic which facilitates assembling a sandwich unit. The chemical coating technology is still under development to optimize reflector durability, thickness and adhesivity. It was found impractical to shield the grooves during etching. After etching a scintillator, including the grooves surface, the white deposit inside the grooves is removed by scraping along the groove profile. The scraping die also forms the groove to an optimum U-shape cross-section. Then the groove surface is rubbed by a solvent to obtain a polished transparent surface suitable for accommodating fibers. A colorless silicone grease was used as an optical couplant between the fibers and scintillator in the tests of single slabs.

3. Test results of single counters

The light yield of the counters was measured with cosmic rays. Fibers of 1 mm diameter are read out on both ends via FEU-115M photomultipliers [7], which have a photocathode sensitivity extended in the green light region, appropriate to detect the WLS fiber light. The fibers used in all tests have a length of 4.3 m. We tested single-clad BCF-92 and multi-clad BCF99-29AA (Bicron) fibers. Their decay time is about 3.3 ns, and the attenuation length is about 4 m at distances of more than 1 m.

The first sample tested was a 2 m long slab with a 19 mm spacing between grooves. The scintillator with embedded multi-clad BCF99-29AA fibers was wrapped in one layer of Tyvek white paper. The total light yield from both ends was about 11.2 ± 0.5 photoelectrons (p.e.) per minimum ionizing particle (MIP) within a range of 1.5 m within the scintillator length, i.e. it did not depend significantly on the position along the counter. The light propagation velocity was measured to be 5.8 ns/m.

Then, the extruder spinneret was modified to produce scintillators with 10 mm spacing between the grooves. The tested samples were 1 m long. 14 multi-clad WLS fibers were embedded in the grooves, and a single layer of Tyvek paper was used as a reflector. The total light yield from both ends was measured to be 17 p.e., or about 12 p.e./MeV.

The next step was to apply the new etched reflector instead of the Tyvek paper. Prepared in this way a 1 m long counter produced a light yield of 19.6 p.e. per MIP, i.e. about 14 p.e./MeV. The ADC spectra obtained in the center of the plastic are shown in Fig. 2. Embedding single-clad BCF-92 fibers reduced the light output of the chemical etched sample by 24%, to 14.9 p.e. per MIP. Further reduction of the spacing between the grooves also increases the light yield. For a spacing of 7 mm, the light yields of about 26 p.e./MIP and 20.8 p.e./MIP were measured with multi-clad and single-clad fiber readout, respectively.

A 7 mm thick counter made of BC404 scintillator was also tested. It was chemically etched and the grooves were cut with 7 mm spacing by a

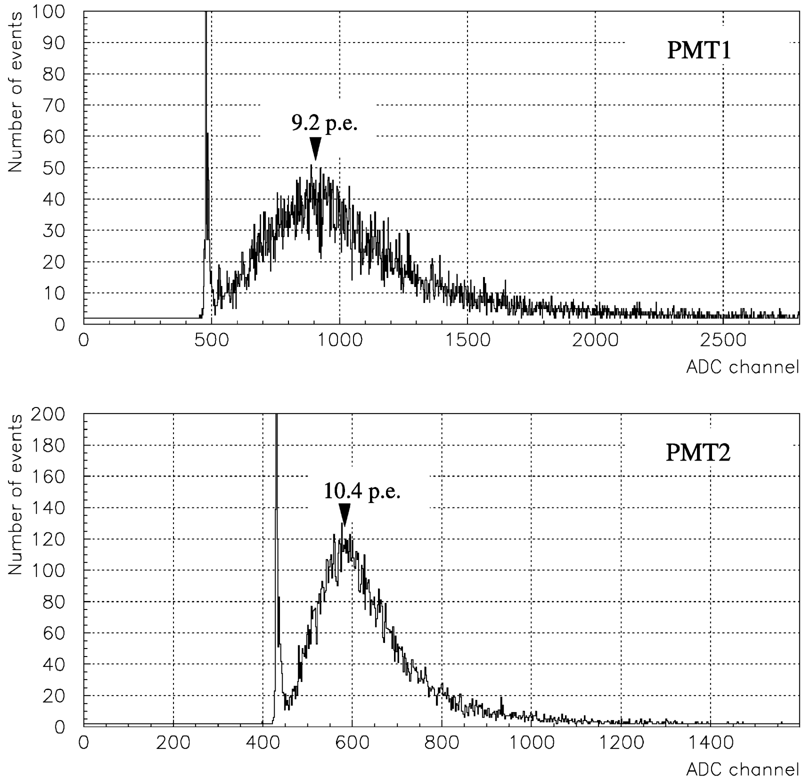

Fig. 2. ADC spectra for both ends of the counter with 10 mm spacing between the grooves. The spectra are taken for cosmic rays traversing the center of a 1 m long plastic scintillation counter.

scraper. The light yield was measured to be 32 p.e./MIP, i.e. 23% more light output than for the polystyrene extruded plastic with the same fiber readout.

Constant-fraction discriminators with a threshold set at a level of about 1 p.e. were used to obtain the timing performance of the counters. The start signal was triggered by a fast plastic while the stop signals were produced by the FEU-115Ms. A time resolution of 0.85 ns (rms) for cosmic particles was obtained (Fig. 3) for a chemically etched sample with 10 mm spacing for multi-clad BCF99-29AA readout. For single-clad BCF-92 readout the resolution was 0.87 ns. Time resolution for the sample with 7 mm spacing is about 0.71 ns (rms) with multi-clad readout, and 0.76 ns with single-clad fibers. It is interesting to note that single-clad fibers with spacing of 7 mm provide a comparable light yield to multi-clad ones with spacing of 10 mm with improved timing.

A 1 m long thin extruded slab of 3 mm thickness manufactured with the chemical etched reflector was also tested. 14 multi-clad BCF99-29AA fibers were embedded in the 1 mm depth grooves, which run with 10 mm spacing. We obtained the light yield of 8.5 p.e. per MIP and time resolution of 0.92 ns (rms). As expected, the measured light output is strictly proportional to the plastic thickness. The results of measurements of the extruded counters are summarized in Table 1.

4. Sandwich module performance

The barrel photon veto detector in E926 will consist of many layers of 7 mm plastic scintillator slabs of 4 m length interleaved by 1 mm thick lead. About 90 lead–plastic layers in the case of 1 mm lead will provide a thickness of 17–18 radiation lengths. Since the visible fraction of deposited

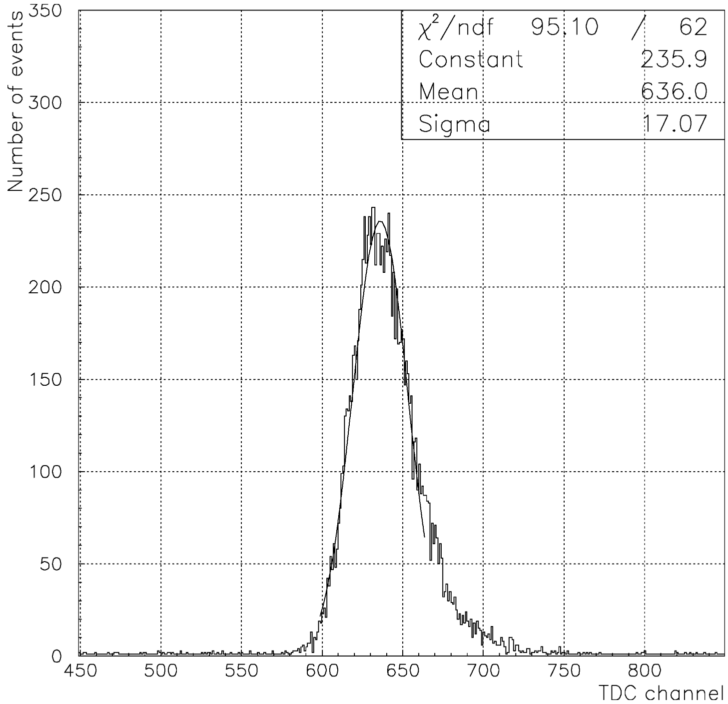

Fig. 3. Time spectrum of the counter with 10 mm spacing between the grooves. Time is measured as average between TDC stops of both PMTs for cosmic rays traversing the center of the scintillator. Scale: 50 ps/ch.

Table 1
Parameters of extruded polystyrene counters with 4.3 m long WLS fiber readout. The counter made of BC404 scintillator is also shown for comparison

Counter thickness (mm)	Spacing (mm)	Fiber type	Light yield (p.e./MIP)	σ_t (ns)
7	19	multi-clad	11.2	
7	10	multi-clad	19.6	0.85
7	10	single-clad	14.4	0.87
7	7	multi-clad	26.2	0.71
7	7	single-clad	20.8	0.76
3	10	multi-clad	8.5	0.92
7 (BC404)	7	multi-clad	32	0.65

energy increases with reduction of the thickness of the lead plates, the first 20 layers of the veto system will be made of thin foils of 0.5 mm each to produce a light yield for low energy photons as high as possible. The whole veto system will be formed of sandwich veto modules, each of which consists of 10 scintillator slabs and 10 lead layers. Such a module will have a length of 4 m, a width of 15 cm and a thickness of about 8 cm. A schematic total view of the sandwich veto module is shown in Fig. 4.

For the tests the prototype has a shorter length of 1 m while the length of the fibers is 4.5 m, i.e. about the length of fibers in the real detector. Ten

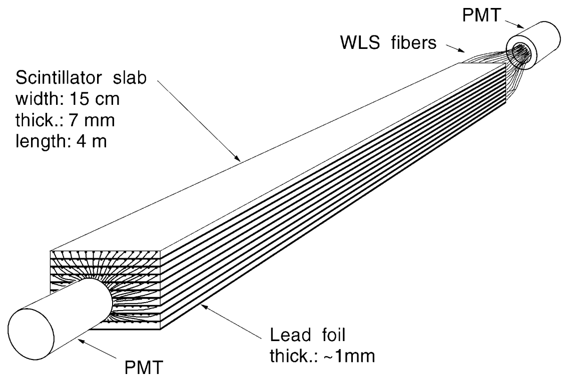

Fig. 4. Schematic view of a sandwich module.

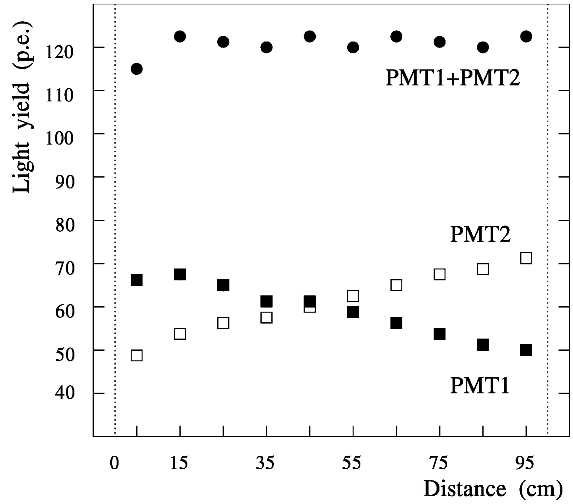

Fig. 5. Light yield uniformity along the sandwich module. The distance is measured from the left module edge.

layers of 7 mm thick extruded plastic slabs and 1 mm lead plates were fixed together in a monolithic block by an elastic polyurethane glue. The module is protected by a 0.1 mm stainless steel container. Single-clad BCF-92 fibers were glued in the grooves with 10 mm spacing. Although multi-clad fibers produce more light their cost is 1.7 times more than the cost single-clad fibers of the same type. Our measurements indicate that the time resolution obtained with fast single-clad WLS fibers is practically the same as for the multi-clad ones. Taking into account a huge quantity of fibers required for the set-up we plan to use multi-clad fibers only for the most sensitive parts of the veto system, where maximum light yield is crucial to reach a high efficiency. A chemical composition based on a polystyrene solution was used as a glue. 140 fibers are compressed in the collets on both ends of a fiber bundle and coupled to FEU-115M phototubes.

The light yield was measured to be 122 p.e. per MIP, i.e. 12.2 p.e. for a single layer. This result is 18% smaller than we obtained in the tests of a single plastic counter with the same single-clad fiber readout. This light yield drop is attributed to the glue, which showed worse transparency than a conventional silicon grease used in the above tests of the single slabs. The overall measured time resolution was obtained to be 440 ps (rms). Taking into account the time spread contribution from the trigger counter (250 ps) the time resolution contribution of the sandwich module is calculated to be 360 ps. Light yield nonuniformity along the module was measured in 10 cm steps. As shown in Fig. 5, the light yield was stable with deviation $\pm 1\%$ from the average over the 90 cm length. The attenuation length was evaluated to be 2.4 m.

An approximate formula for the resolution of a typical scintillator-Pb sampling calorimeter [8] is

$$\sigma[\%] = \frac{14.5}{\sqrt{E_\gamma[\text{GeV}]}}\sqrt{\frac{t}{X_0}}\sqrt{1 + 0.57/n},$$

where t is the thickness of the lead plates, X_0 is the radiation length of lead, and n is the number of photoelectrons per minimum ionizing particle in a single scintillator layer. If $n \geqslant 5$, the impact of photostatistics is negligible on the energy resolution, which is dominated by sampling fluctuations. For a thickness of 1 mm lead we expect to obtain energy resolution of $\sigma \sim 6.1\%/\sqrt{E_\gamma}$ for our veto modules.

Extrapolating the time parameters obtained for this module, the time resolution of the veto detector is estimated to be close to 220 ps (rms) for a 100 MeV photon, or 70 ps$/\sqrt{E_\gamma[\text{GeV}]}$. The time response resulted in an evaluation of position resolution along fibers to be close to 4.0 cm for a 100 MeV photon. The resolution in the other direction is defined by the 15 cm width of the modules, i.e. 4.3 cm.

5. Conclusion

Extruded polystyrene scintillator counters with WLS fiber readout were manufactured and tested with cosmic rays. The extruded plastic produces 80% of the light from PVT-based BC404 scintillator. Light yield of ~ 19 p.e./MeV and time resolution of 0.71 ns in a single scintillation layer of 7 mm thickness with BCF99-29AA double-clad WLS fibers of 4.3 m length were obtained. A prototype photon veto module consisting of 10 layers of 7 mm thick plastic slabs interleaved with 1 mm lead sheets was also tested. Single-clad BCF-92 fibers of 4.5 m length spaced at 10 mm were used for the readout. The module yielded 122 photoelectrons per minimum ionizing particle and time resolution of 360 ps.

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